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A Comparison of Transient-Radiation Effects Vulnerability Analysis with Experimental Results

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A low-cost analytical method has been used by the Harry Diamond Laboratories for the past several years to assess the response of U.S. Army electronic equipment to transient-radiation effects (TRE). A series of experiments was designed to test several assumptions inherent in the methodology.

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20. ABSTRACT (Cont'd)

The results of experiments on three circuits to determine their vulnerability to neutron radiation are compared to previously determined analytic vulnerabilities. Large sample sizes (~100) give good statistical data and demonstrate that the analytic method results are reasonable. Reasonable results improve the confidence that low-cost analytic vulnerability estimates can be made for systems used in the tactical nuclear environment.

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FIGURES (Cont'd)

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1. INTRODUCTION

In a theater nuclear war tactical equipment could be exposed to nuclear radiation. Many Army tactical systems contain electronic equipment and may, therefore, be vulnerable when exposed to this nuclear environment. During the past several years at the Harry Diamond Laboratories (HDL), more than 60 pieces of Army electronic equipment have been analyzed to determine their response to the transient-radiation effects (TRE) caused by the neutron and gamma radiation.[1-5,*]

The methodology used in the first phase of the above-mentioned HDL program to determine the equipment vulnerability is strictly analytic. The analysis is very conservative, so that if the equipment is hard nothing further need be done; however, if the equipment is not hard, testing is done and the equipment hardened if required. The testing and hardening is done in a second phase program. To increase the users' confidence in the validity of the assumptions inherent in the analysis methodology, a series of verification tests was devised and performed. This report describes the results of these verification tests whose objective was to demonstrate that the analytic techniques used to predict neutron response in the tactical system vulnerability analyses realistically predict circuit performance in a radiation environment.

The analysis methodology consists of several steps. Basically these are identifying the semiconductors and their response to radiation at set screen levels, determining the circuit performance with degraded

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[1] *P. A. Trimmer, J. M. Vallin, R. A. Polimadei, and C. T. Self, Vulnerability of Army Electronic Equipment to TRE (AN/GRC-46, AN/GRC-142, PRC-77) (U), Harry Diamond Laboratories, HDL-PR-78-1 (November 1978). (CONFIDENTIAL)*

[2] *P. A. Trimmer and R. A. Polimadei, Vulnerability of Army Electronic Equipment to TRE: AN/GRC-50, AN/GRC-103, CV-1548/G (U), Harry Diamond Laboratories, HDL-PR-78-2 (October 1978). (CONFIDENTIAL)*

[3] *P. A. Trimmer, Vulnerability of Army Electronic Equipment to TRE: AN/GRC-144, AN/PPS-5(A), AN/MPQ-4(A) (U), Harry Diamond Laboratories, HDL-PR-79-1 (November 1979). (CONFIDENTIAL)*

[4] *W. L. Vault and P. A. Trimmer, Vulnerability of Army Electronic Equipment to TRE: Multichannel and Radio Teletypewriter Sets (U), Harry Diamond Laboratories, HDL-PR-79-4 (December 1979). (SECRET-RESTRICTED DATA-NOFORN)*

[5] *P. A. Trimmer, Vulnerability of Army Electronic Equipment to TRE: TH-22/TG, TD-352/U, TD-353/U, SN-421/TPX-50, C-7651, and RT-9031/TPX-50 (U), Harry Diamond Laboratories, HDL-PR-80-3 (July 1981). (CONFIDENTIAL)*

**P. A. Trimmer, Vulnerability of Army Electronic Equipment to TRE (CP-936/TPX-50 and AN/MPA-49) (U), Harry Diamond Laboratories, to be published. (CONFIDENTIAL)* components, and estimating the neutron fluence, gamma dose, and peak gamma rate at which the circuit no longer functions reliably. Figure 1 shows the major steps in the analysis.

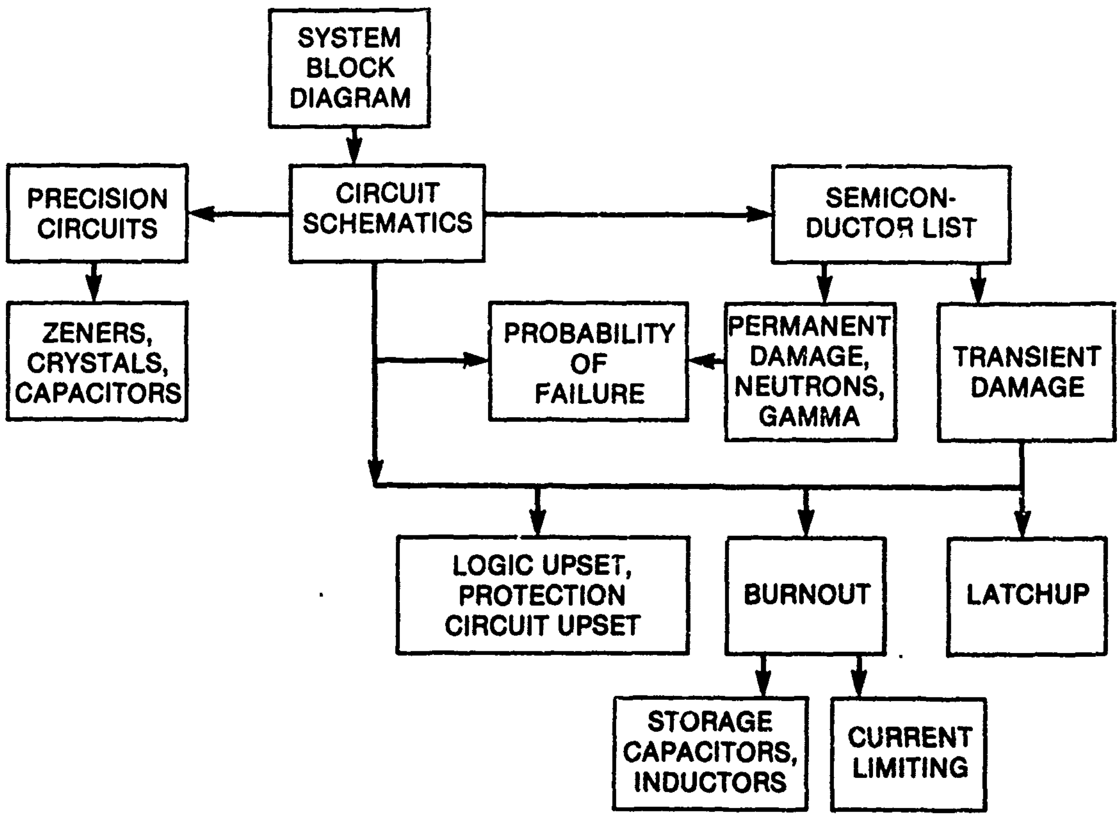

Figure 1. Block diagram of steps in radiation effects vulnerability analysis of Army electronic systems.

2. TEST PROCEDURE

The verification tests were done in five steps. First, selected circuits previously analyzed were constructed, and their performance was measured and compared with that found from analysis. The circuits selected for these tests were the MD522 modulator-demodulator (modem) 20-V regulator (fig. 2), the AN/GRC-103 radio 28-V regulator (fig. 3), and the AN/GRC-103 radio baseband amplifier (fig. 4).

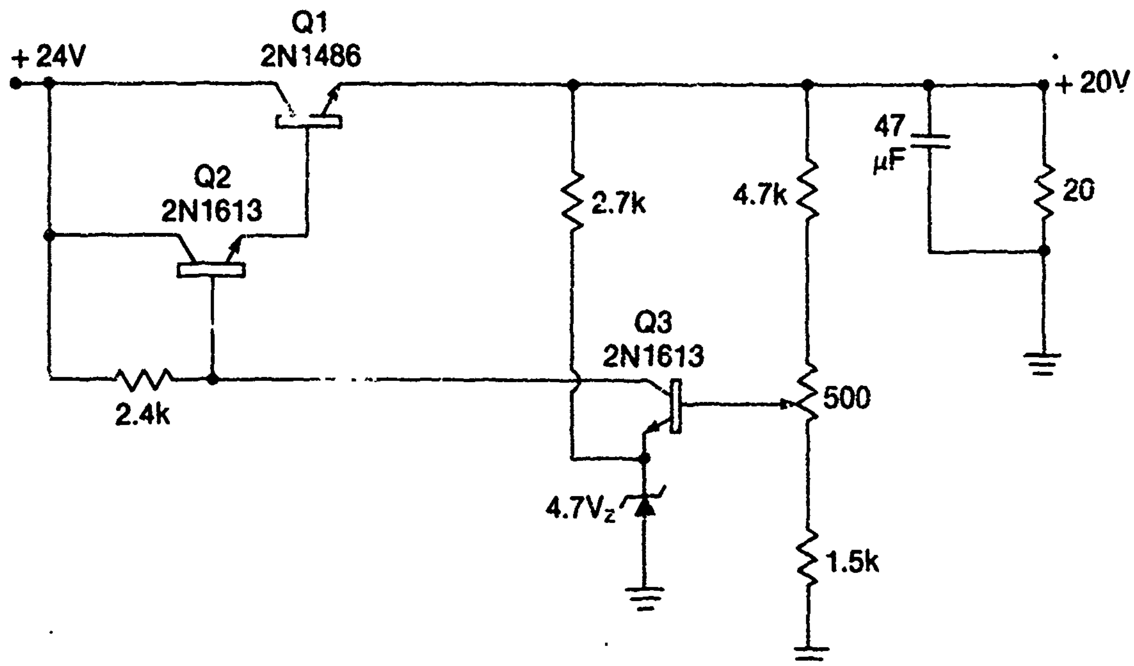

Figure 2   Schematic of 20-V regulator used in MD522 modem.

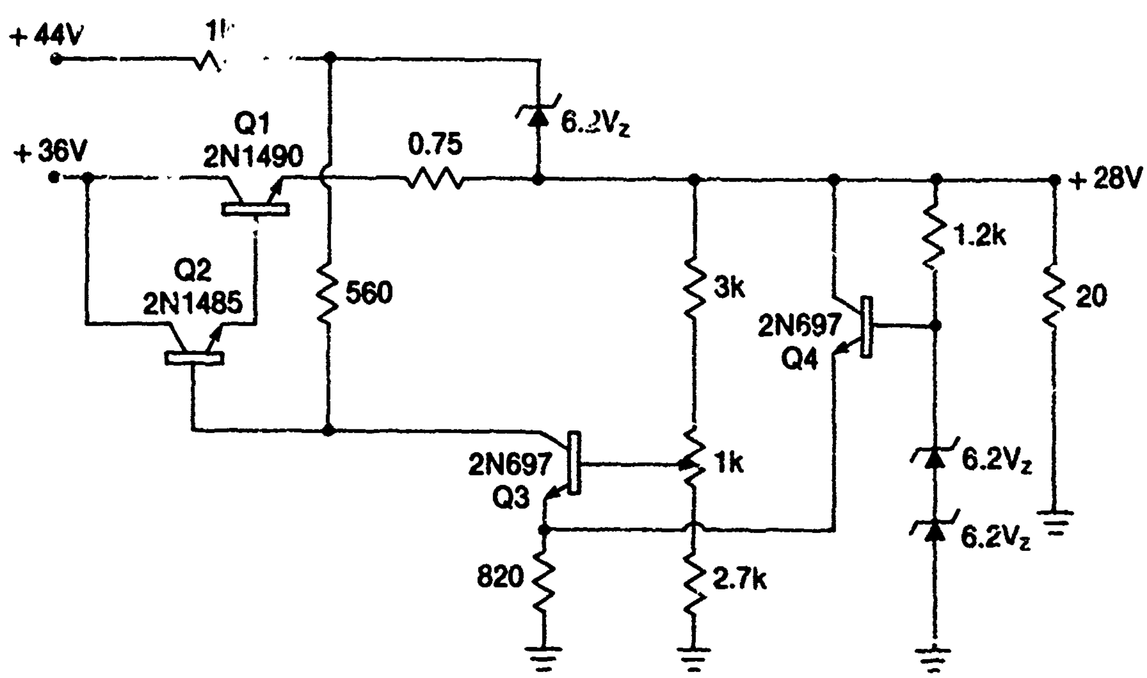

Figure 3. Schematic of 28-V regulator used in AN/GRC-103 radio.

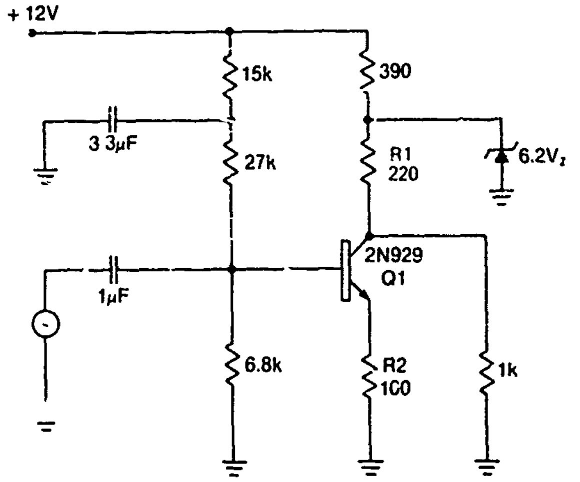

Figure 4. Schematic of baseband amplifier used in AN/GRC-103 radio.

Second, approximately 100 of each type of transistor used in these circuits were obtained for the tests. The transistors' parameters were measured and parameter statistics calculated. The parameter statistics for the test samples were compared with either those statistical data obtained from the HDL Component Response Information Center (CRIC) or calculated data (whenever there were no CRIC data for a device type) that was used in the analysis. Statistical tests of the means and variances were made; fits of the sample distribution to normal and lognormal distributions were tested; and the data were compared to each other.

Third, these large samples of transistors were irradiated, and the degraded transistor parameters were compared with those used in the analysis.

Fourth, the irradiated transistors were inserted into the circuits, and the transistor gain at the threshold of failure, β_T, was determined. Once β_T was determined, failure histograms for the circuits were constructed based upon the distribution of β's in the sample population.

Fifth, the measured-probability-of-failure curves were compared with the predicted-probability curves (fig. 5).

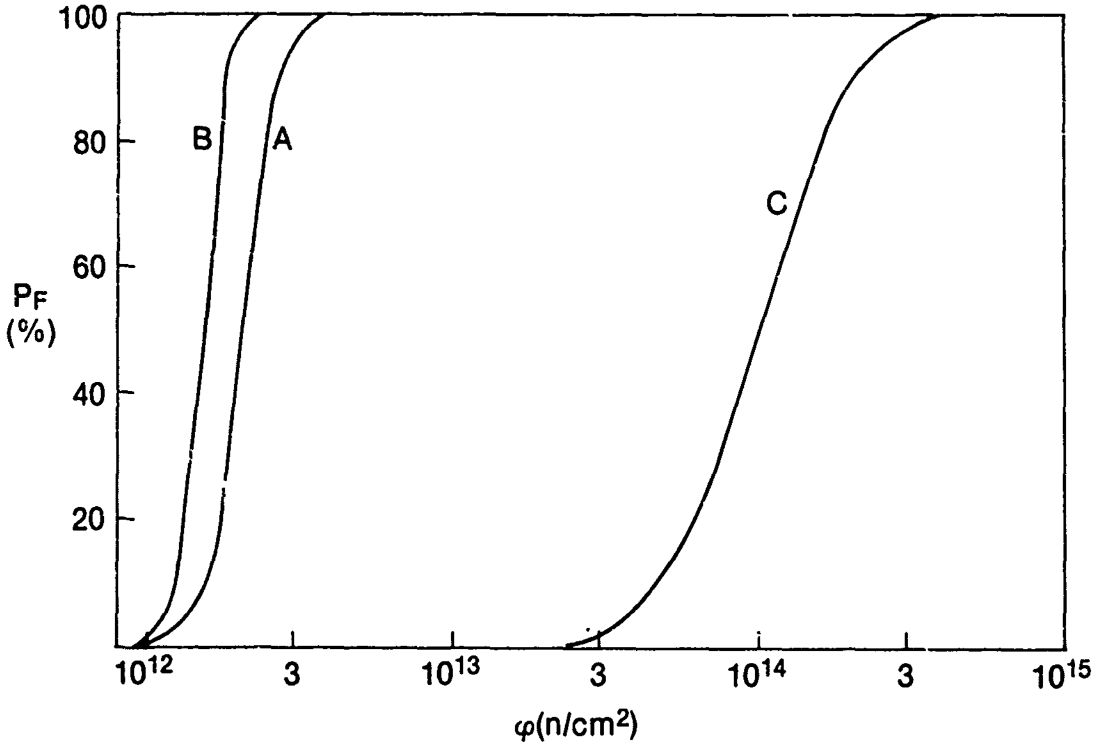

Figure 5. Predicted probabilities of failure for three circuits used for verification test: (a) 20-V regulator, (b) 28-V regulator, and (c) baseband amplifier.

3. CIRCUIT OPERATION

3.1 20-V Regulator

The proper operation of the 20-V regulator shown in figure 2 is a function of two factors: the load current (in this case 1 A) and the combined gains of transistors Q1 and Q2. The large test sample of transistors had a distribution of gains (β's). Because of this distribution in β, various combinations of transistors could be inserted into the circuit in order to obtain a curve (fig. 6) of output voltage versus $\beta_{Q1} \times \beta_{Q2}$. The lower values of β used to calculate the product were obtained by irradiating the transistor until the desired value of degraded β was obtained. The two curves, analysis and experimental, shown in the figure agree very well; for both curves, the output voltage starts to degrade at a combined gain of about 1000. Failure of the circuit is defined as a voltage drop of about 2 percent, which corresponds to $\beta_{Q1} \times \beta_{Q2} = 900$.

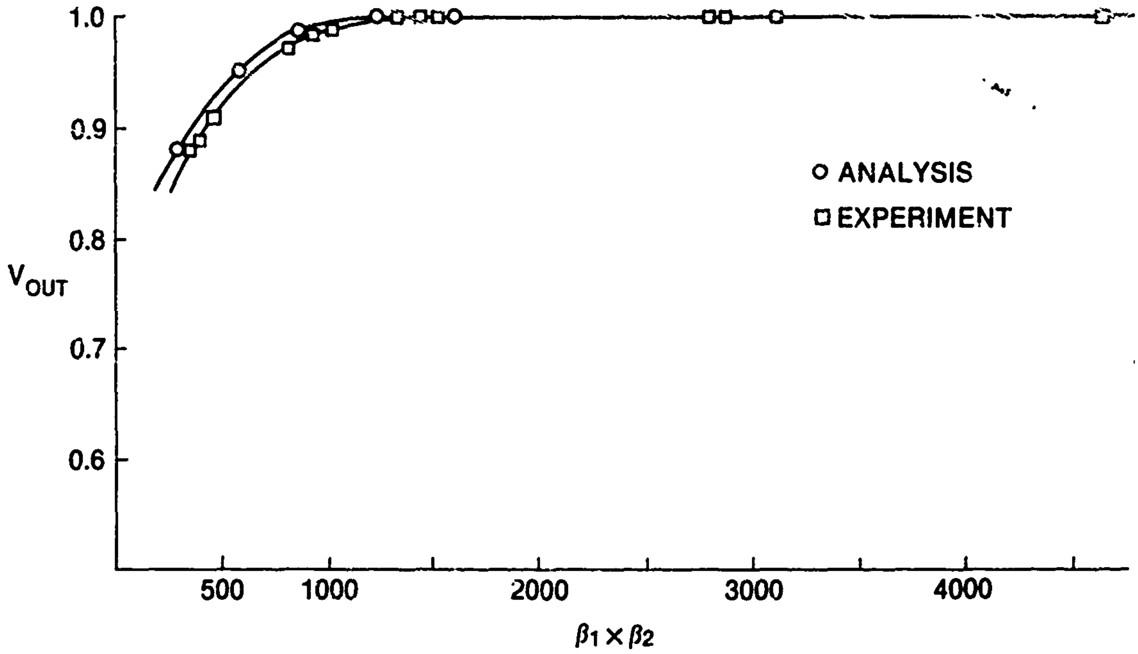

Figure 6. Normalized output voltage of 20-V regulator as function of combined gains of series and drive transistors.

In general, the exact point of system/circuit failure is difficult to define. For this circuit it could be defined as the level that the output voltage is out of specification, or it could be defined as the level at which the circuits whose voltages are supplied by this regulator fail to operate properly. This latter level is actual failure, but it is often very difficult to determine, unless the equipment is available to test and a considerable amount of testing is done. However, for these verification tests, any point on the curve could be selected for this purpose.

The transistor β degrades when irradiated by neutrons. In the 20-V regulator, β of the 2N1613 (Q2) degrades 10 to 15 percent at a fluence of 1 × 10^{12} n/cm^2, and β of the 2N1486 degrades about 75 percent. For this circuit, the critical parameter is the product $\beta_{Q1} \times \beta_{Q2}$. Thus, the 2N1486 is the critical transistor when irradiated in determining the degradation of the product of gains. Obviously, the initial gain of the 2N1613 is also important, however, since the higher the initial gain, the more the 2N1486 can degrade before circuit failure.

3.2 28-V Regulator

The proper operation of the 28-V regulator (see fig. 3) also depends on the value of the load current (1.4 A) and the combined gains of Q1 and Q2 (series and drive transistors). Both transistors (2N1490 and 2N1485) degrade 60 to 70 percent at 1×10^{12} n/cm^2. Figure 7 is a plot of the measured and calculated response of this circuit. For this circuit the threshold for failure is more easily determined. As shown in the figure, the output voltage rapidly drops off once $\beta_{Q1} \times \beta_{Q2}$ becomes less than 200. The failure threshold was set at 170.

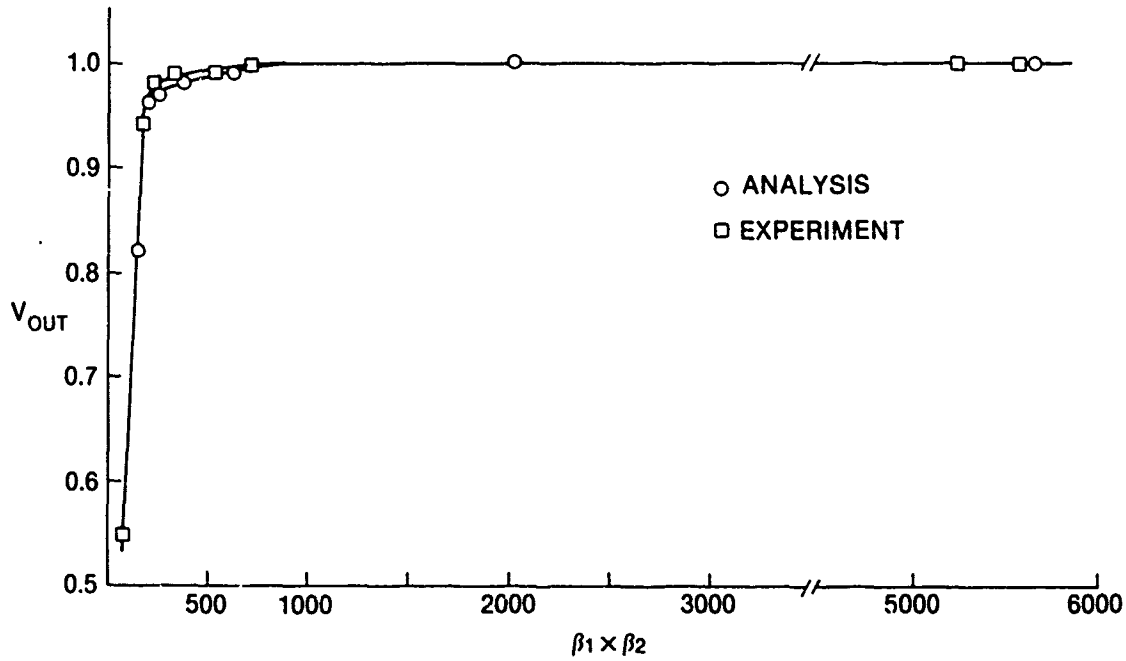

Figure 7. Normalized output voltage of 28-V regulator as function of combined gains of series and drive transistors.

3.3 Baseband Amplifier

The proper operation of the baseband amplifier shown in figure 4 is a function of the β of Q1. The normalized amplifier gain versus transistor gain for the baseband amplifier is plotted in figure 8. Until β_{Q1} becomes less than 40, the stage gain is determined mostly by R1 and R2. Failure for this amplifier is defined as a 3-dB loss, which occurs when $\beta = 9$. This type of circuit failure is difficult to determine in communication equipment. To do so requires actual use of the equipment to determine whether the signals are readable under all conditions. Therefore, engineering judgement must be used in this case.

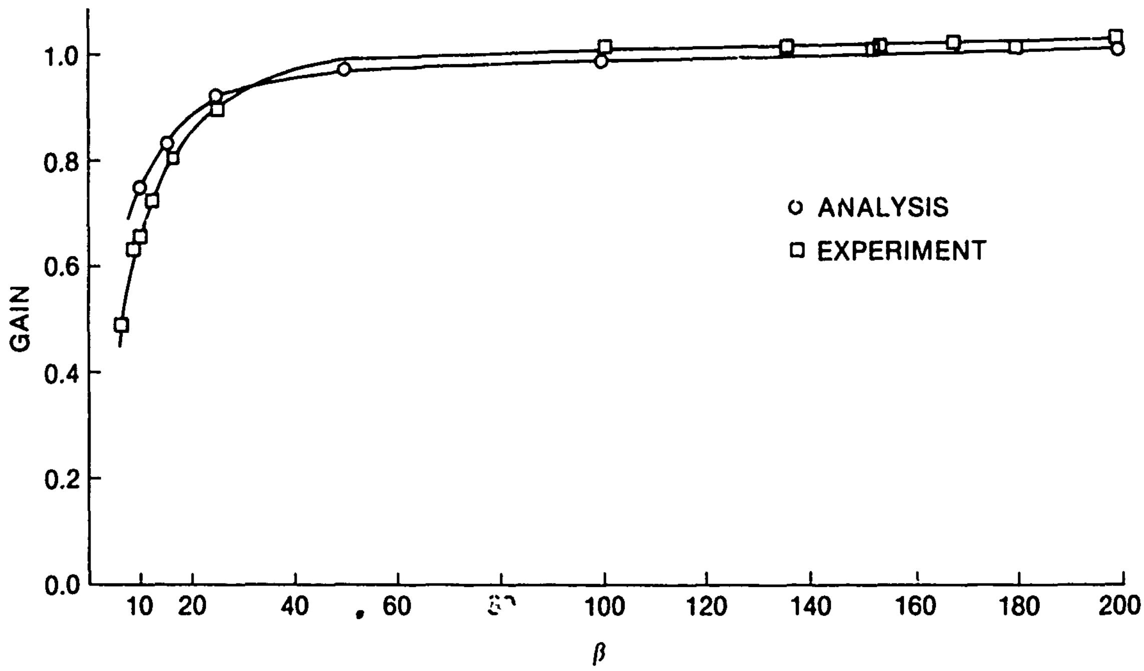

Figure 8. Normalized gain of baseband amplifier as function of transistor gain.

As seen in figures 6, 7, and 8, the calculated and measured circuit operations agree very well. This is not unexpected for relatively simple circuits such as the 20- and 28-V regulators and the baseband amplifier.

4. TRANSISTOR STATISTICS

4.1 Goodness of fit

The second and third steps in the test procedure were to determine the statistics of the unirradiated and irradiated transistors.* Figures 9 and 10, examples of these statistics, show the β_0 distribution of 94 unirradiated 2N1490's and the β_ϕ distribution after irradiation at 2.2×10^{12} n/cm^2 (fig. 10). These data were obtained at a collector current of 1.4 A. Similar data were taken on 89 2N1485's, 90 2N1486's, and 90 2N929's (fig. 11 to 16). The 2N1630 is not included in the goodness of fit because of the small sample size.

Joseph Michalowicz of HDL was very helpful in advising on the statistical analysis presented here.

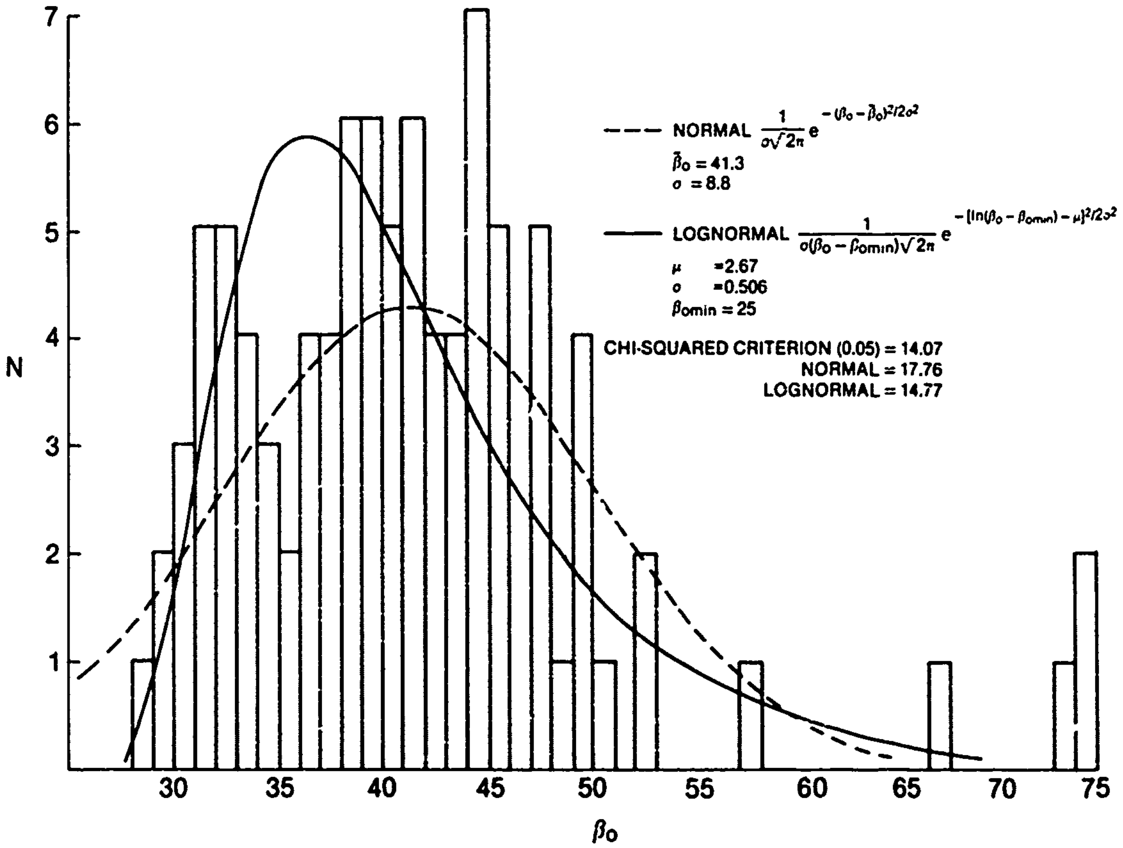

Figure 9. Distribution of 94 2N1490 transistors at zero neutron fluence.

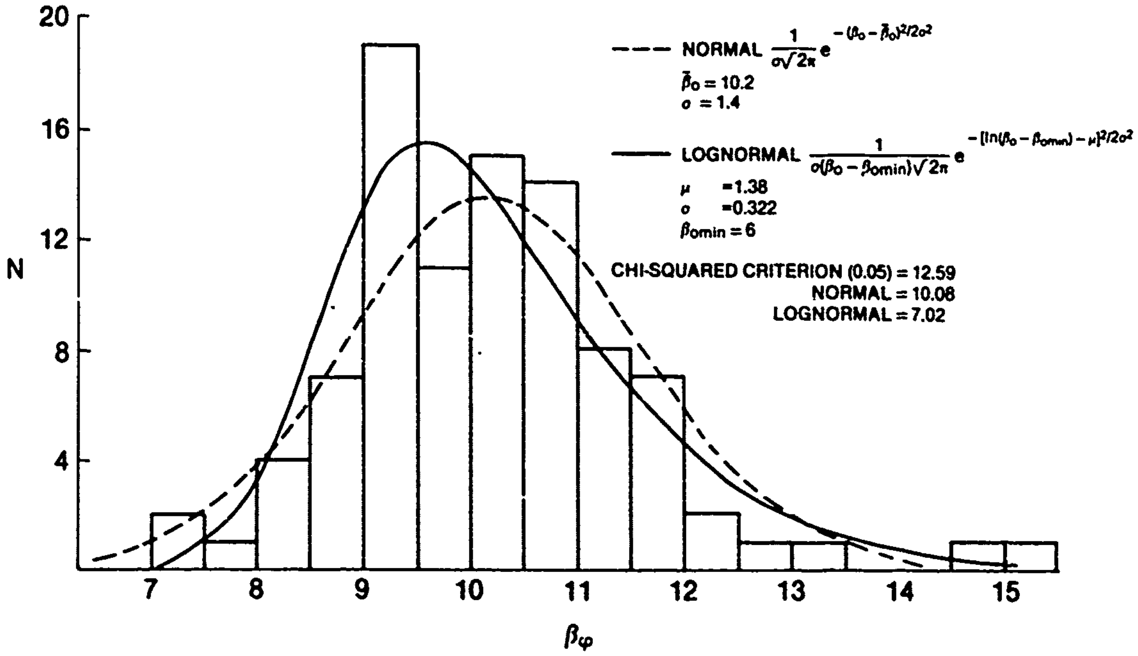

Figure 10. Distribution of 94 2N1490 transistors after being exposed to neutron fluence of 2.2×10^{12} n/cm^2.

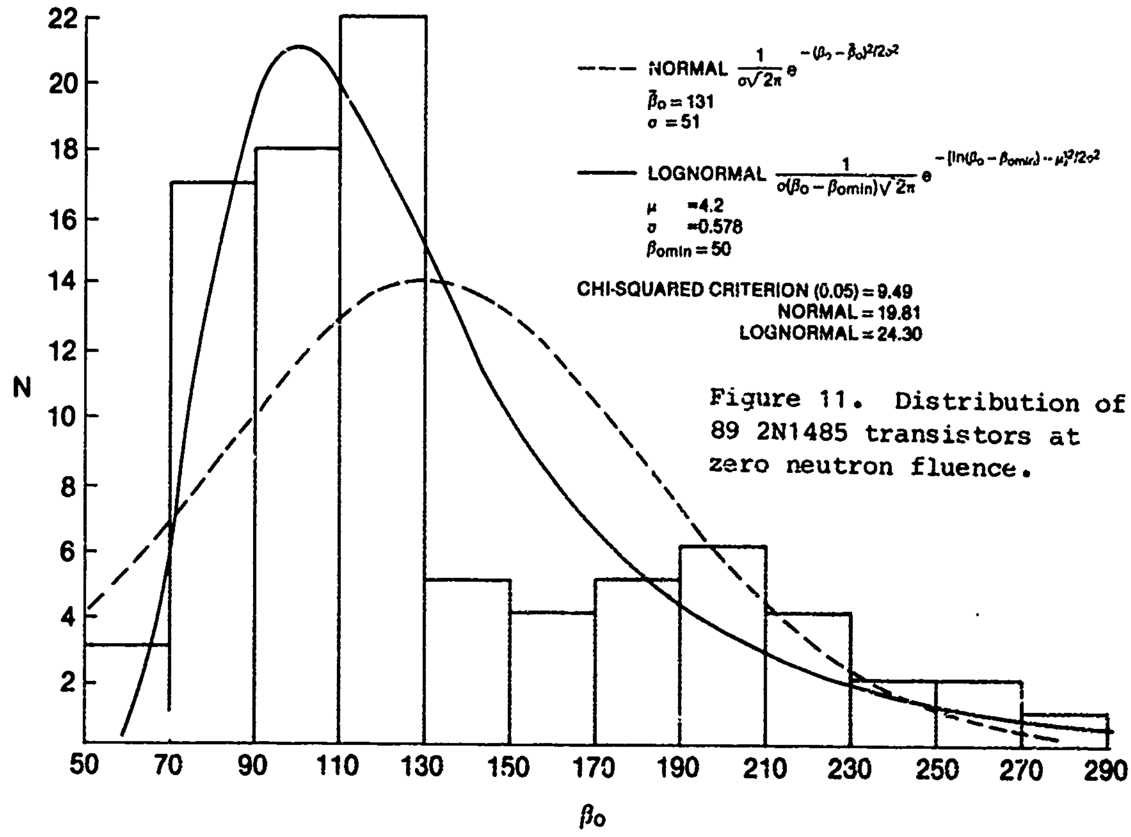

Figure 11. Distribution of 89 2N1485 transistors at zero neutron fluence.

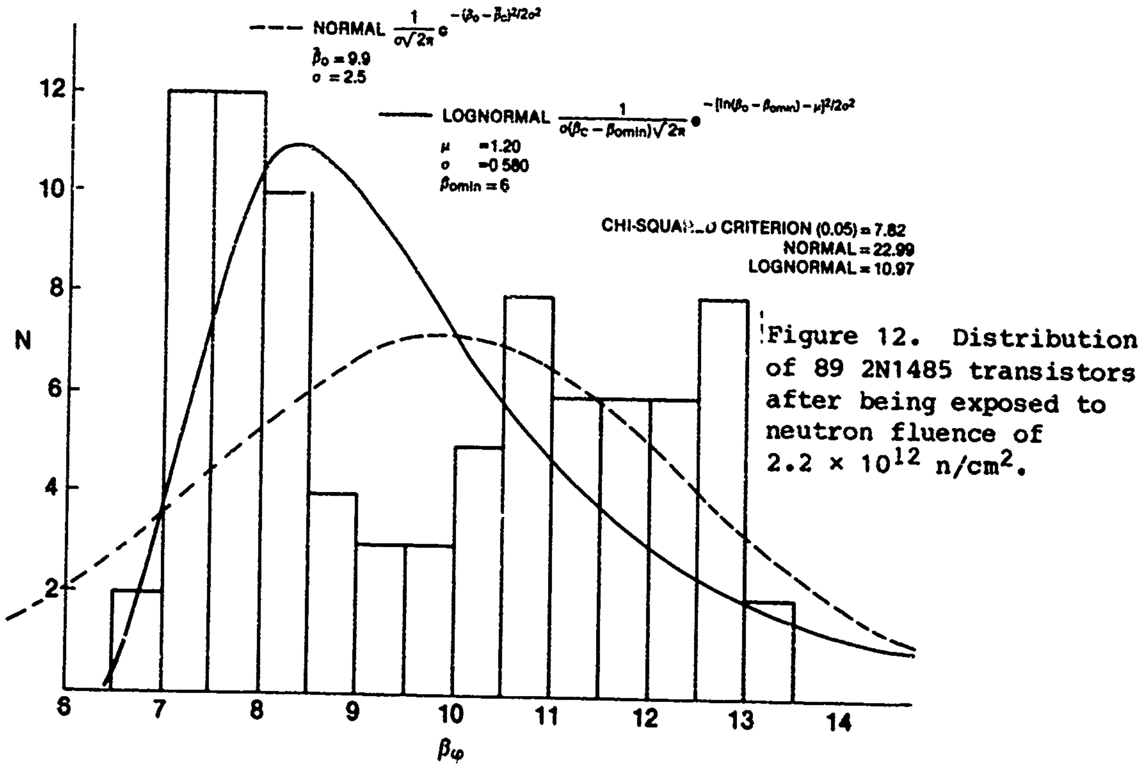

Figure 12. Distribution of 89 2N1485 transistors after being exposed to neutron fluence of 2.2×10^{12} n/cm^2.

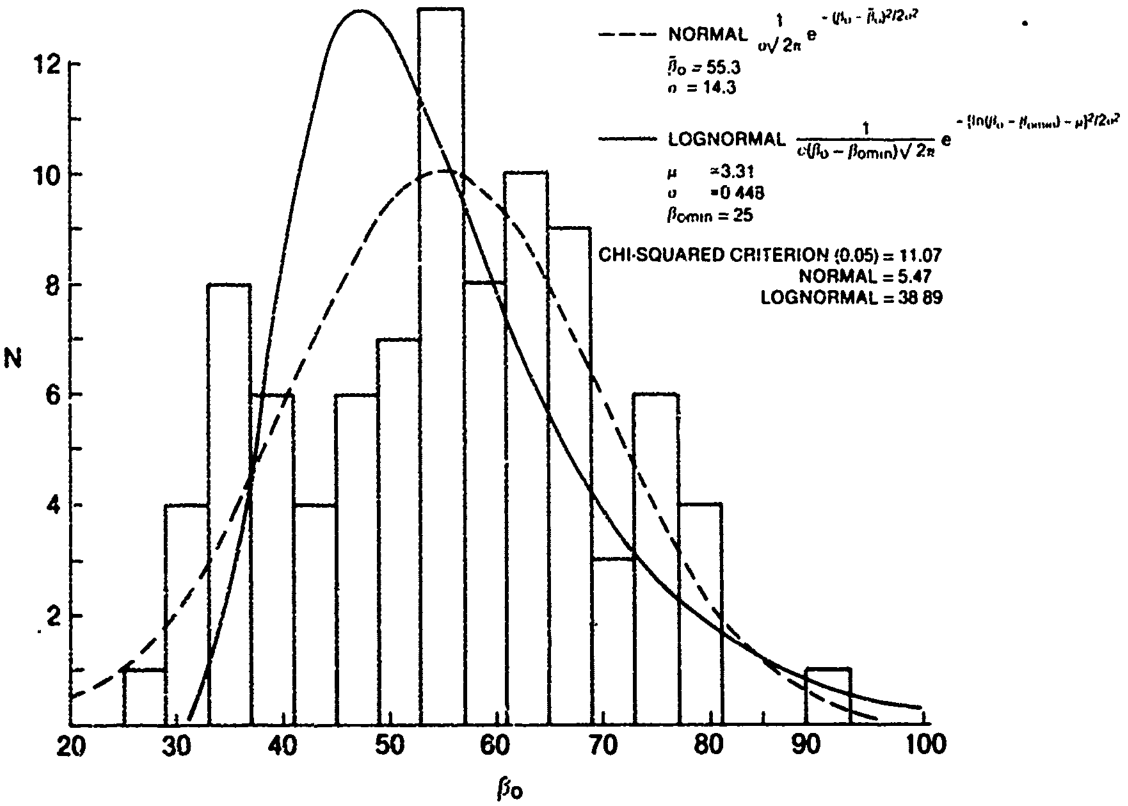

Figure 13. Distribution of 90 2N1486 transistors at zero neutron fluence.

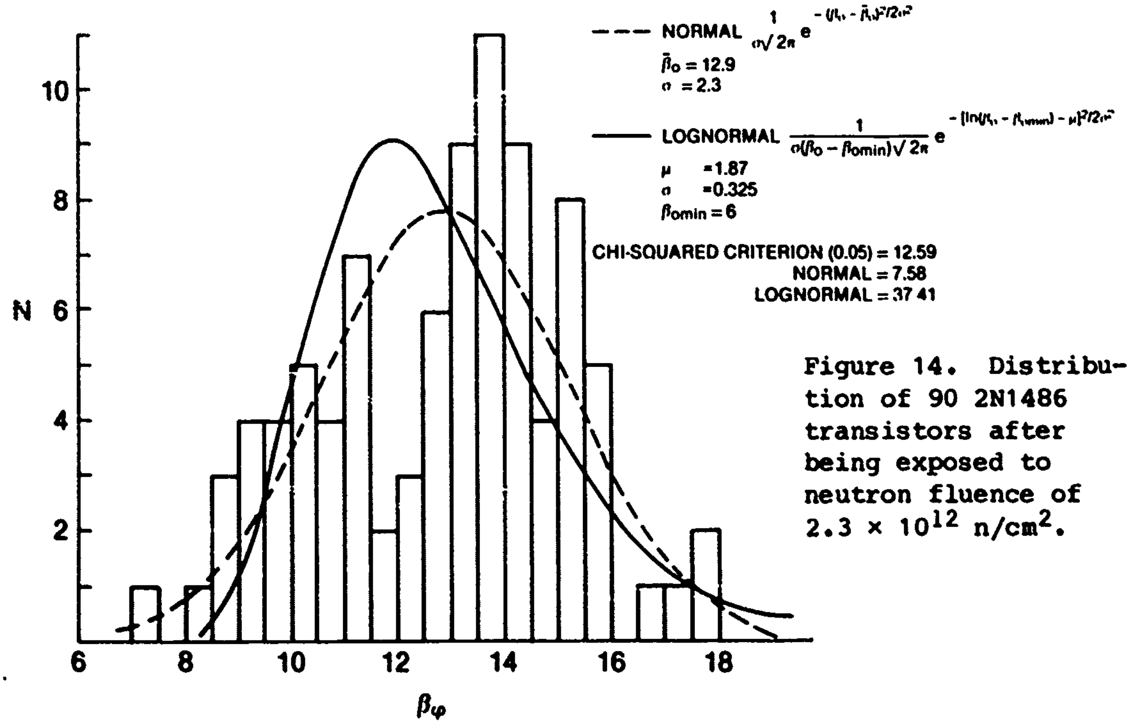

Figure 14. Distribution of 90 2N1486 transistors after being exposed to neutron fluence of 2.3×10^{12} n/cm^2.

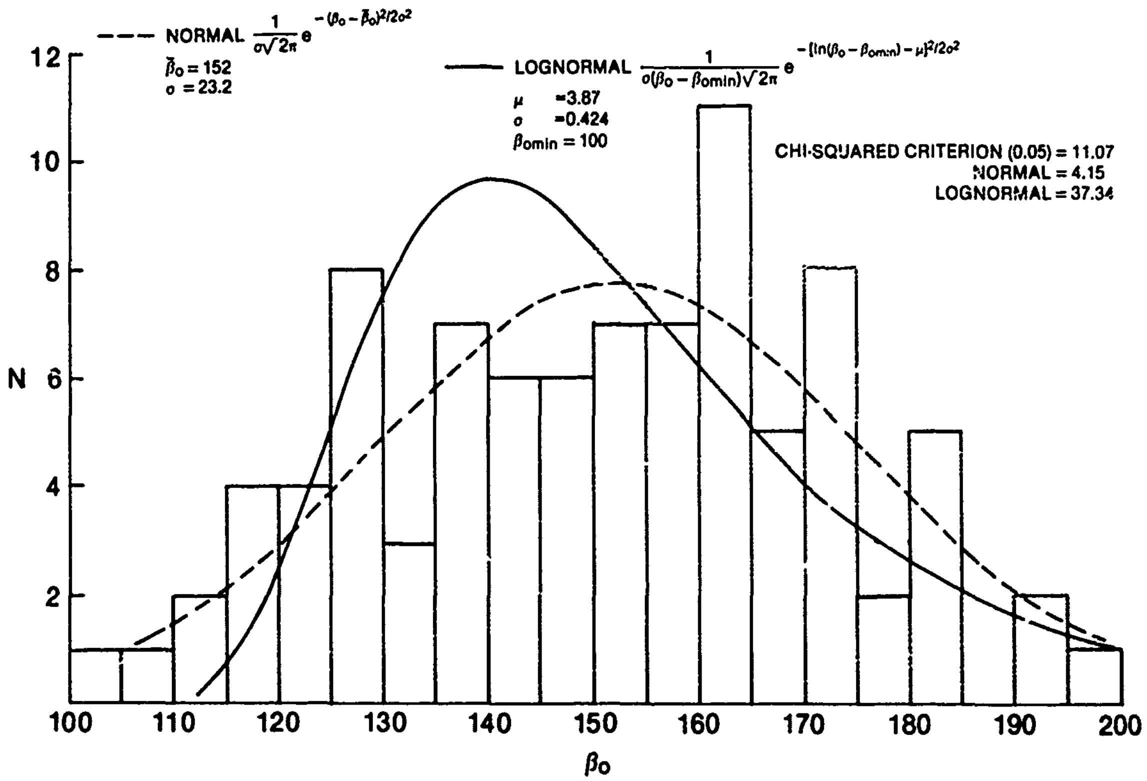

Figure 15. Distribution of 90 2N929 transistors at zero neutron fluence.

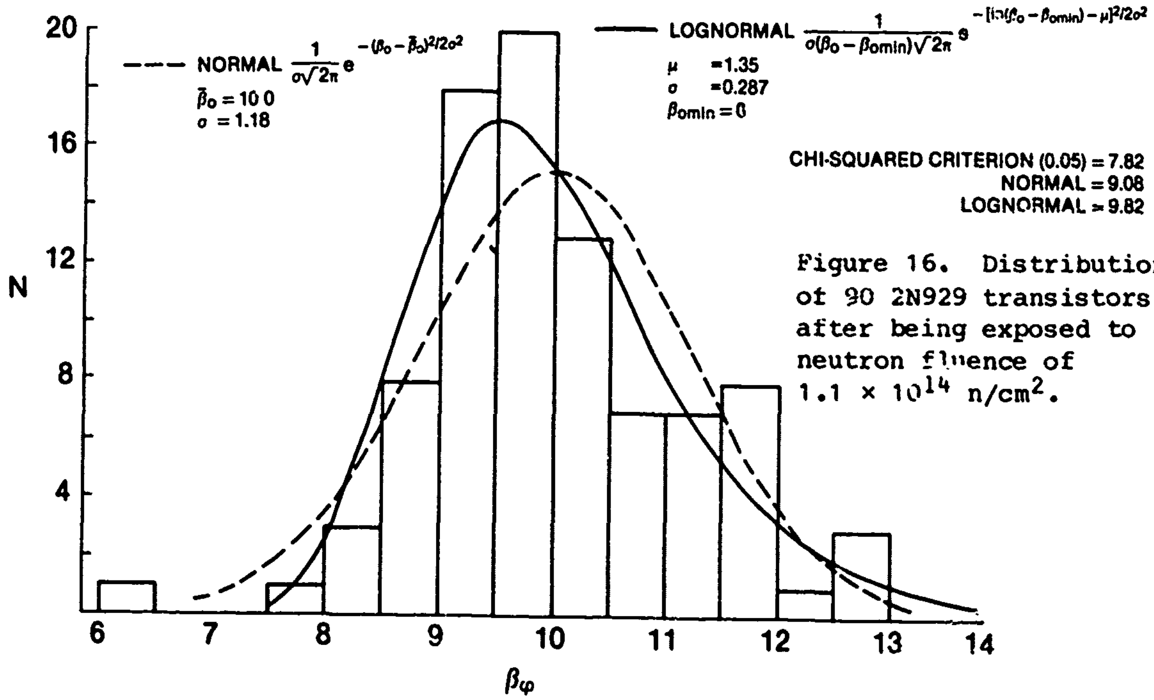

Figure 16. Distribution of 90 2N929 transistors after being exposed to neutron fluence of 1.1×10^{14} n/cm^2.

These data were fit to a normal distribution and to a truncated lognormal distribution. The chi-squared test was applied to determine the goodness of fit, where goodness of fit is concerned with a statistical hypothesis that a set of observed values represents a random sample from a particular distribution. Although the form of a test statistic and its distribution differ from one procedure to another, all procedures are based upon the fact that the distribution of the distribution function for any probability tends to be uniform. Thus, for common values of the random variable, a test is formed based upon differences between the observed distribution function for the sample data and the hypothesized one. If the test statistic is small enough, the null hypothesis is accepted, implying that there is no observed evidence of a poor fit; if it is too large, the null hypothesis is rejected, implying a poor fit.

Among the better-known techniques for goodness-of-fit analysis are the chi-square,[6] Kolmogorov-Smirnov,[7,8] and Cramer-von Mises tests.[7] The procedure used in this investigation is described by Green and Margerison.[9] The chi-squared number at a 95-percent level of significance, shown for the normal and lognormal fits in each figure (9 to 16), was obtained from

$$\chi^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i} ,$$

where k is the number of pairs of frequencies to be compared and o_i and e_i denote the ith pair of observed and expected frequencies. A value of zero corresponds to exact agreement between observation and expectation. When the number is greater than the chi-squared criterion (0.05), the probability that the curve does not represent the sample population is greater than 5 percent. Of the eight sets of data, four of the normal curves show results greater than the chi-squared criterion (0.05), and four show results less than this criterion. For the lognormal curves, the results show that seven are greater than the criterion and one is less. Although these results can be interpreted to imply that the normal curve is a better fit, the conclusion reached here is that neither distribution is a good fit of the data, and that the reason that

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[6] *W. G. Cochran, The χ^2-Test of Goodness of Fit, Ann. Math. Stat., 23 (1962), 315-345.*

[7] *D. A. Darling, The Kolmogorov-Smirnov, Cramer-von Mises Tests, Ann. Math. Stat., 28 (1957), 823-838.*

[8] *H. W. Lillefors, On the Kolmogorov-Smirnov Test for Normality with Mean and Variance Unknown, J. Am. Stat. Assoc., 62 (1967), 699-402.*

[9] *J. R. Green and D. Margerison, Statistical Treatment of Experimental Data, Physical Science Data 2, Elsevier Scientific Publishing Company, New York (1978).*

the lognormal curve is used by many people is probably that the population density looks more lognormal than normal due to the positive skewness.

4.2 Test on Means and Variances

The fourth step in the test procedure was to compare the statistical mean μ and variance σ of two sets of transistor data: that used in the analysis with that determined in these tests. Table 1 lists the two sets of data for the five transistor types used in the three circuits. If we assume that β_0 and β_ϕ are approximately normally distributed, we can test the means of the two sets of data--analysis and experiment--by using

$$Z = \frac{\bar{x} - \bar{y} - \mu_{x-y}}{\sigma_{x-y}} ,$$

where

$\bar{x}$ = mean of sample x,

$\bar{y}$ = mean of sample y,

μ = mean of population,

$$\mu_{x-y} = \mu_x - \mu_y$$

$$\sigma_{x-y} = \left(\frac{\sigma_x^2}{N_x} + \frac{\sigma_y^2}{N_y}\right), \text{ and}$$

σ = standard deviation of population.

If the two samples are from the same population, then $\mu_x = \mu_y$ and $\mu_{x-y} = 0$.

There is some error introduced by estimating the population values μ_x and μ_y from the sample value(s) when the true values are unknown. Table 2 lists the value of Z for the five transistor types. If we use a 2σ value of 1.96 as the critical point, we must, for all the transistors except the 2N929, reject the hypothesis that the two samples come from the same population. This rejection is understandable, considering that (1) one set of data was obtained more than 5 years before the other, and (2) many variables enter into the manufacture of transistors. However, both samples still fit the criteria for that type of transistor; that is, they fall within the guaranteed β_{min}, β_{max}, and other ratings.

TABLE 1. TRANSISTOR DATA USED IN ANALYSIS AND EXPERIMENT

Transistor	Current (mA)	Fluence (n/cm^2)	Parameter[a]	Analysis	Experiment
2N1486	1000	0	β_0	49.1	55.3
			S	6.1	14.3
			N	8	90
	1000	2.3×10^{12}	β_ϕ	13.2	12.9
			S	1.6	2.3
			β_{min}	8.7	7.4
			β_{max}	18.2	17.9
			K_D	2.4×10^{-14}	2.6×10^{-14}
2N1630	30	0	β_0	78.4	65.6
			S	9.6	17.0
			N	10	26
	30	1.9×10^{12}	β_ϕ	64.9	54.6
			S	7.9	10.8
			β_{min}	41.6	39.9
			β_{max}	88.6	80.4
			K_D	1.4×10^{-15}	1.6×10^{-15}
2N1490	1400	0	β_0	37.0	41.3
			S	6.0	8 [illegible]
			N	10	94
	1400	1.9×10^{12}	β_ϕ	6.6	11.5
			S	1.1	1.6
			β_{min}	4.1	8.0
			β_{max}	9.9	17.1
			K_D	6.6×10^{-14}	3.3×10^{-14}
2N1485	50	0	β_0	84.0	131
			S	15.0	51.0
			N	8	89
	50	1.9×10^{12}	β_ϕ	20.0	11.6
			S	3.6	2.9
			β_{min}	10.8	7.7
			β_{max}	30.8	25.1
			K_D	2.0×10^{-14}	4.1×10^{-14}
2N929	10	0	β_0	150	152
			S	41.0	23.2
			N	10	90
	10	1.1×10^{14}	β_ϕ	8.9	10.0
			S	2.4	1.2
			β_{min}	--	--
			β_{max}	--	--
			K_D	1.0×10^{-15}	8.8×10^{-16}

[a]*Symbols*

β_0 = average initial gain
S = standard deviation of sample
N = number of transistors
β_ϕ = average gain after irradiation
β_{min} = minimum gain
β_{max} = maximum gain
K_D = damage factor

TABLE 2. RESULTS OF TESTING MEANS OF GAINS OF TRANSISTORS USED IN ANALYSIS AND EXPERIMENT

Transistor	Z
2N1613	2.84
2N1490	2.04
2N1485	6.21
2N1486	2.36
2N929	0.15

The variances of the two samples were tested using the F distribution given by

$$F = \frac{\dfrac{N_x S_x^2}{N_x - 1}}{\dfrac{N_y S_y^2}{N_y - 1}} .$$

Table 3 lists the results of this test. The five and the one percentile areas of the F distribution are shown for comparison. Again, as with the means, the conclusion that these variances are from the same population must be rejected.

TABLE 3. RESULTS OF TESTING VARIANCES OF β OF TRANSISTORS USED IN ANALYSIS AND THOSE USED IN EXPERIMENTS[a]

Device	F	v	F(5%)	F(1%)
2N1613	2.94	9, 25	2.28	3.21
2N1490	1.96	9, 93	1.98	2.60
2N1485	10.2	7, 88	2.11	2.84
2N1486	4.86	7, 89	2.11	2.84
2N929	3.43	9, 89	1.89	2.60

[a]*Symbols:*

v = degrees of freedom ($N_x - 1$) and ($N_y - 1$).

F(5%) = 5th percentile area of F distribution.

F(1%) = 1st percentile area of F distribution.

Although the tests do not show that the transistors used in the analysis and in the experiment come from the same population, the data are relatively consistent. For example, a review of the entries for damage factor K_D (under "Parameter") in table 1 indicates that values for analysis and experiment are close for all except the 2N1490 and the 2N1485 transistors. The damage factors for both of these are a factor of two apart, which is not unusual for transistor parameters.

5. FAILURE ANALYSIS

The final two steps in the procedure were determining (1) the operation of the circuits containing the irradiated transistors and (2) the probability of failure, where the probability of failure is the fraction of transistors with β less than β_T at a given fluence. Figures 6, 7, and 8, comparisons of analysis and experiment, show the effect of irradiated transistors on circuit performance. Figures 17, 18, and 19 are similar comparisons for the probability of failure. For example, figure 17 compares the predicted failure for the 20-V regulator (see fig. 5) with experiment; figure 18 compares the predicted failure of the 28-V regulator with experiment; and figure 19 does the same comparison for the baseband amplifier. The agreement between analysis and experiment appears to be very good. It is obvious that the standard deviations of the two sets of data for the baseband amplifier (2N929) differed a large amount. In fact, as shown in table 1, they are a factor of two apart.

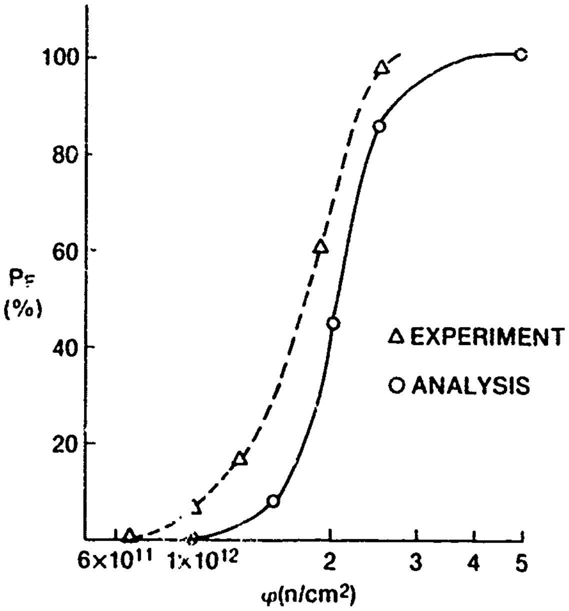

Figure 17. Experimental and calculated probability of failure for 20-V regulator.

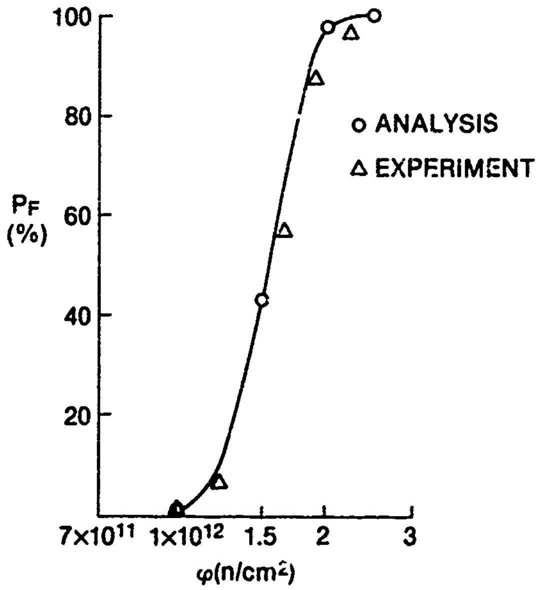

Figure 18. Experimental and calculated probability of failure for 28-V regulator.

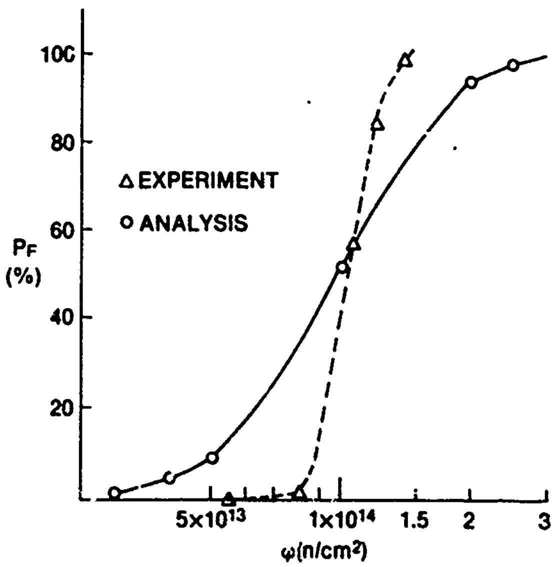

Figure 19. Experimental and calculated probability of failure for baseband amplifier.

Figure 17 appears to contradict the contention that the analysis is conservative. Actually, when circuit response is determined, the attempt is made to predict as accurately as possible the response to radiation. The conservativeness comes in the system failure criteria, worst-case radiation scenario, radiation level at which further testing is done, and the disregard of annealing that occurs after radiation.

6. DISCUSSION AND CONCLUSIONS

These tests have shown the reasonableness of the methodology used to analyze the nuclear vulnerability to permanent damage by neutrons of Army tactical equipment. The actual failure fluence level of the equipment as used in the field, however, is more difficult to determine, because many circuits do not have sharp failure points, but rather degrade gradually as neutron fluence increases. For example, the output of a power amplifier in a communications receiver may decrease, but the point at which intelligibility ceases may depend on several other factors which are beyond the scope of this analysis, such as noise level, operator skill, and atmospheric conditions. For this reason, the system failure level is done in a conservative safe-side manner that allows some hard systems to initially appear soft, but prevents any soft systems from appearing hard.

The fact that the transistor distributions were found to fit neither normal nor lognormal distributions and that transistors of the same type do not appear to belong to the same populations might be mathematically disturbing, but there are reasonable explanations. This behavior is mostly due to the way that transistors are manufactured and, in some cases, to the way that they are sold. For example, someone may buy a large number of transistors with gains between values x and y. Another buyer, who gets the rest of the devices, would then have a distribution with a hole caused by the extraction of those between x and y. However, as long as the devices meet all specifications they should function satisfactorily in a circuit. Thus, when circuits which include devices from this modified distribution are analyzed for radiation effects, the worst case must be considered along with the average case. The worst case is a transistor with the specified minimum gain, irradiated to the maximum neutron fluence, at the specification low temperature. If the circuit still functions properly, then it is hard, and distribution of gains will make no significant difference to circuit performance.

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